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Fuel Interchangeability Considerations for Gas Turbine Combustion

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ABSTRACT

In recent years domestic natural gas has experienced a considerable growth in demand particularly in the power generation industry. However, the desire for energy security, lower fuel costs and a reduction in carbon emissions has produced an increase in demand for alternative fuel sources. Current strategies for reducing the environmental impact of natural gas combustion in gas turbine engines used for power generation experience such hurdles as flashback, lean blow-off and combustion dynamics. These issues will continue as turbines are presented with coal syngas, gasified coal, biomass, LNG and high hydrogen content fuels. As it may be impractical to physically test a given turbine on all of the possible fuel blends it may experience over its life cycle, the need to predict fuel interchangeability becomes imperative. This study considers a number of historical parameters typically used to determine fuel interchangeability. Also addressed is the need for improved reaction mechanisms capable of accurately modeling the combustion of natural gas alternatives.

INTRODUCTION

Modern, low-emission gas turbines that utilize lean, pre-mixed (LPM) combustion are tuned to maintain cool flame conditions that avoid the formation of NOx pollutants. Gas turbine engines utilizing this technology have shown the ability to produce single digit NOx emissions[1,2]. However, changes within the combustion system have resulted in LPM combustors being more susceptible to undesirable combustion phenomena such as lean blow-out, flashback and combustion instabilities. These conditions are exacerbated further by the effects of fuel variability.

Domestic natural gas supplies are typically composed of greater than 90% methane with small amounts of heavier hydrocarbons (ethane and propane) and inerts such as nitrogen, carbon dioxide and water vapor[3]. Growing economic and environmental pressures have increased interest in the use of alternative to what we know as typical pipeline gas, including coal derived syngas, landfill and biomass gases, imported liquefied natural gas (LNG) and hydrogen augmented fuels (Table 1). Although syngas compositions can vary considerably, these fuels are primarily H_2 and CO, with smaller amounts of CH_4, N_2, H_2O and CO_2[4]. Landfill gases are characterized by lower heating values primarily due to CO2 which can be as high as 40% by volume with the remainder being mostly CH_4 and a balance of N_2[5]. The cryogenic processes used to produce liquefied natural gas (LNG) often results in reduced levels of inerts producing fuels with greater levels of heavier hydrocarbons, thus higher heating values (HHV). Inerts such as nitrogen and air can be blended with "hotter" fuels to reduce the heat values. Given the wide range of compositions these fuels present there is expected to be an influence on combustion.

Table 1: Typical compositions of various fuel blends

	NG	Landfill Gas	Coal Syngas	LNG
CH_4 (%)	92.0	54.5	0.9	89.8
C_2H_6 (%)	3.6	-		7.5
C_3H_8 (%)	0.8	-		2.0
C4+ (%)	1.5	-		0.7
H_2 (%)	-	-	45.0	-
CO (%)	-	-	49.0	-
CO_2 (%)	-	37.5	2.9	-
N_2 (%)	1.8	7.0	2.2	0.2
O_2 (%)	-	1.0		-
Wobbe Index (BTU/scf)	1367	639	450	1415

A number of studies have been published regarding the effects of fuel composition and ambient conditions on gas turbine operation[6]. Recent studies of Flores et al[7] and Hack[8] demonstrated an increase in NOx emissions in a micro-turbine when heavier-hydrocarbons (C2+) were added to conventional pipeline gas in significant quantities. Lieuwen et al[9] and Zhang et al[10] considered how syngas mixtures, rich in hydrogen and carbon monoxide may influence the operability of premixed combustors. Particular emphasis was given to phenomenon such as flashback, lean blowoff and combustion instabilities which have shown some sensitivity to fuel composition. Noble[3] suggested the use of a classical Damkohler number scaling to predict the onset of lean blowoff.

It should not be suggested that engines cannot be adjusted or tailored to operate on widely different fuel composition. Kurz[2] notes that some engines may allow as much as a 10% variation in fuel heating value, while others can accommodate less than 2-3%. Although engines may be adjusted/designed for different fuels, a key question is whether engines that have been designed to meet emissions standards on domestic natural gas can accommodate sudden changes in fuel composition, without causing machine upsets, excess emissions, or component damage.

Fuel interchangeability is often used to describe the ability of substituting one gaseous fuel for another in a combustion application without significantly altering operation and performance[4]. Issues of fuel interchangeability have been a concern from almost the start of the industrial age as town began switching from "manufactured" or "city" to a distributed pipeline natural gas in the 1930's[11,12]. Concerns regarding the effect a substitute gas may have on combustion and burner operation lead to the creation of a number of parameters in an attempt to predict the outcome. These parameters could be classified as either single index or multiple indices methods. Single index parameters focused on relating the energy content of the fuels in question, while the multiple indices attempted to predict some elements of the combustion behavior[13]. Both single and multiple indices were derived from empirical data obtained from thousands of test performed on a range of burner[12]. During the period in which these parameters were derived, the primary end-use for the gas supply was industrial or residential burners operating at atmospheric conditions. Primary concerns for fuel interchangeability at this time were to ensure a consistent heat input, and predict flame lifting or blow-off, flashback, yellow tipping, sooting and carbon monoxide emissions related to incomplete combustion. Today, only industrial use (33%) outweighs power generation (31%) in terms natural gas consumption with residential usage at 21% of the total[14].

As the currently available interchangeability factors were derived from atmospheric burners, there is some concern as to their applicability for gas turbine engines used for power generation. As previously stated, next generation turbines must meet ever increasing NOx emissions standards regardless of the fuel being consumed. Although there have been some recent attempts in predicting the effects of increasing the concentration of heavier hydrocarbons in the fuel on NOx emissions[8], none of the historic parameters address this concern. Furthermore, turbines that utilize LPM technology to meet NOx emissions tend to be more susceptible to lean blow-off, flashback and combustion dynamics. Interchangeabilities factors such as Wobbe number, which is still commonly used today, do not specifically address combustion related phenomena, and while factors do exist for flashback and blow-off, their applicability for pressurized gas turbine combustion is unclear. To address the need for the prediction of fuel gas interchangeability in modern high pressure gas turbine engines, the Natural Gas Council convened the NGC+ task group in 2005. This group produced a series of interim guidelines which were published in the NGC+ white paper[15] that applied strict limitation on Wobbe number, fuel heating value and inert gas concentration.

This paper provides a brief evaluation of the use of existing interchangeability prediction methods for use in fuel flexible gas turbine applications. A basic review of several of these common indices is provided along with some discussions with regards to current recommendations. A brief experimental analysis on the use of these parameters to predict changes in the onset of combustion dynamics is presented. Followed by conclusions and some discussion on the use of modern computational tools to better predict fuel interchangeability.

Interchangeability Models

In response to the growing concerns over fuel interchangeability the Natural Gas Council formed the NGC+ Work Group on Interchangeability. The result of their work was published in a white paper with the objective of defining an acceptable range of fuel gas characteristics[15]. Based on their findings a series of interim guidelines, shown graphically in Figure 1, were obtained. These guidelines suggested a range of +/- 4% from the local historical average gas, subject to a maximum Wobbe number of 1400 and a maximum heating value of 1100 BTU/ft^3. Additionally fuel compositions limits were placed on butanes, with a maximum of 1.5% by volume, and inerts which were limited to 4% by volume. These guidelines are demonstrated in Figure 1 plotting the higher heating value (HHV) versus the specific gravity based on the US Average Wobbe value of 1345 reported in the 1992 Gas Research Institute (GRI) survey. This results in +/-4% Wobbe values of 1400 and 1291, respectively. Trend lines end at the recommended maximum HHV of 1100 BTU/ft^3. Fuels described in Table 1 are also shown for reference with an additional blend of pipeline NG (Wobbe = 1367), typical LNG import blend (Wobbe = 1415) and the same LNG import blended with the recommended maximum of 4% inert nitrogen (Wobbe = 1347) and blended with 1.5% nitrogen to reach the recommended HHV maximum of 1100 BTU/ft^3 (Wobbe = 1392).

Although these guidelines are based largely on Wobbe number, there is some concern as to its applicability to predict performance important to today's combustion equipment, particularly gas turbine engines. This point was also address by the NGC+ work group suggesting that while gas interchangeability indices, such as Wobbe number, represent the best starting point for developing guidelines there are some significant limitations to the relying solely on Wobbe number and additional specifications may be necessary.

Work in the area of fuel effects on specific combustion phenomena important to gas turbine combustion, such as combustion dynamics, flashback, lean blow-off and NOx emissions continues as evident by recent works by Hack et al[8] and Lieuwen et al[9]. These works address the issue of fuel flexibility and interchangeability, and attempt to provide predictive tools for NOx emissions based on the content of C1, C2 and C3 hydrocarbons in the fuel[8] or utilizing the Damköhler number (ratio of residence time to chemical time scale) to predict lean blow-out[3]. However, while the research community pursues much needed updated parameters, gas suppliers and end-users continue to utilize historical interchangeability parameters as a means of qualifying a particular fuel blend. To this end, the remaining of this paper reviews several historical single index parameters and there applicability to modern LPM gas turbine engines.

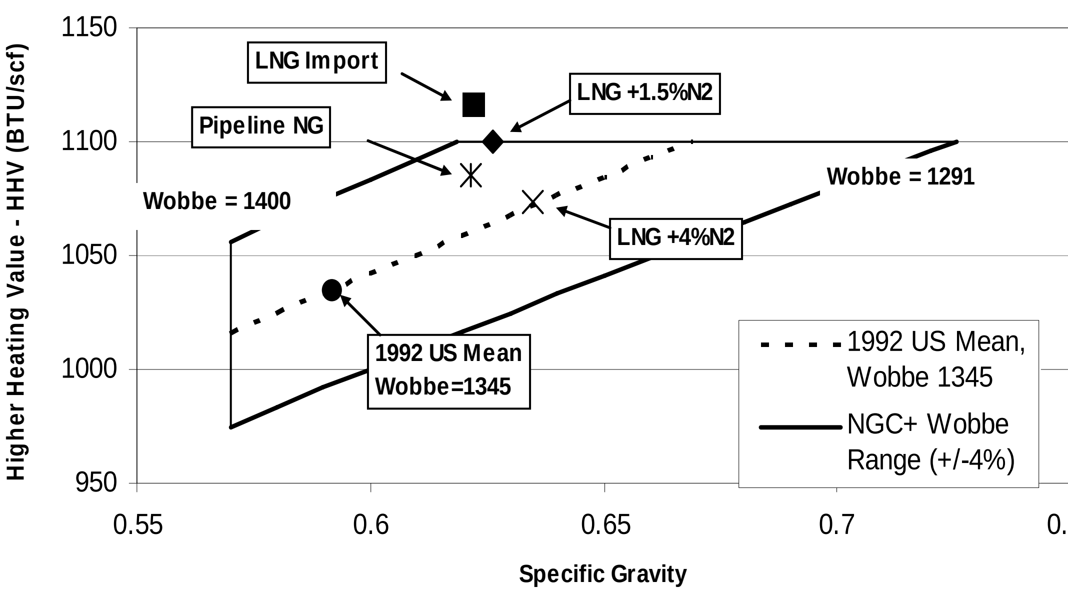

Figure 1: US Average Natural Gas supply with NGC+ Work Group Interim Guidelines

Interchangeability Factors

Wobbe Index

The Wobbe index is a single index parameter that by itself is a measure of the heat input of a fuel to a given burner design and is defined by the following equation

$$Wobbe = \frac{HHV}{\sqrt{SG}} \tag{1.1}$$

where HHV is the higher heat value given in BTU/ft^3 or MJ/m^3, and SG is the specific gravity of the gaseous fuel. The use of the specific gravity allows for the generalization of a range of fuels to a specific burner give a constant pressure drop and fixed orifice size in the fuel injector. As gas appliances are designed for a given thermal input, the Wobbe number provides a sufficient measure for this application. However it is not intended to be a measure of overall interchangeability. This may be even more significant for gas turbine engines as they are typically controlled for turbine inlet temperature and Wobbe index is not a good indicator of flame temperature.

Schuster Index

The Schuster index represents an early attempt to measure the effects of varying fuel composition on combustion and not limited to just the thermal input of the fuel[16]. The Schuster index is a ratio of the heat input of the fuel, as measured by the Wobbe index, to the rate of heat production or burning velocity (S_u)

$$S_c = \frac{Wobbe}{S_u} \tag{1.2}$$

The use of this parameter has been limited, due in part to the lack of availability of reliable flame speeds at the time of its derivation. Since that time reliable experimental data has been obtained for many individual constituents such as methane, ethane, propane, etc. As conventional pipeline natural gas has been an area of interest and relatively constant for some time, kinetic mechanisms obtained in part from empirical results of the flame speed data of the individual constituents have shown to be accurate. Flame speeds measurements for alternative fuels such as coal derived syngas, landfill gases and imported LNG have not experienced the same level of evaluation. Although flame speed data is readily available for the individual constituents that make up these fuels, derivation of the kinetic mechanisms is not trivial. Lieuwen et al[9] discussed the difficulty in dealing with fuel mixtures as opposed to individual constituents due to differences in transport and thermodynamic properties of the mixtures. However, accurate kinetic mechanisms are becoming available[17] and thus the Schuster Index may prove to be a more comprehensive single index parameter.

Weaver Indices

The Weaver indices is a set of multiple indices that include lifting, flashback and yellow tipping and additional parameters for heat input ratios, primary air ratios and incomplete combustion (CO). Through these indices, Weaver[11,16] attempted to reliably predict interchangeability for high-BTU gases, while maintaining reasonable accuracy for low-BTU gas. Similar to the Schuster Index, the foundation of the Weaver's empirically derived indices is the inclusion of a flame speed parameter. The Weaver indices for primary air ratios, lifting, flashback and the Weaver Flame Speed Factor are given below, where A is the stoichiometric air, Q is the molar fraction of oxygen in the mixture, a_i is the molar fraction of combustible component i, B_i is the empirically derived Weaver flame speed coefficient, and Z is the molar fraction of inerts in the gas mixture. The subscript "a" indicates the primary or "adjustment" gas while terms without the subscript are for the "substitute" gas. Fuel interchangeability is predicted based on the limits that give a relative correlation of the "Substitute" fuel to the "adjustment" gas.

Given the progress made in flame speed measurements since the derivation of these indices in 1951, replacing the Flame Speed Factor with predicted flame speeds based on current kinetic models may improve the usefulness of these parameters.

$$\text{Primary Aeration Index: } J_A = \frac{A}{A_a}\left(\frac{S_a}{S}\right)^{1/2} \quad \text{Limit: 0.8 - 1.2}$$

$$\text{Lifting Index: } J_L = J_A \frac{S}{S_a}\left(\frac{100-Q}{100-Q_a}\right) \quad \text{Limit: } \geq 0.64$$

$$\text{Flashback Index: } J_F = \frac{S}{S_a} - 1.4J_A + 0.4 \quad \text{Limit: } \leq 0.26 \qquad (1.3)$$

$$\text{Weaver Flame Speed Factor: } S = \frac{\sum a_i B_i}{A + 1.0 + 5.0Z - 18.8Q}$$

Experimental Analysis

The lab-scale burner is a ring-stabilized premixed burner that is inserted into a quartz-tube. The quartz (Rijke) tube has an 8.0 cm diameter and an 80 cm length (see Fig. 2). This Rijke tube arrangement produces acoustic feedback that interacts with the heat-release rate in the flame to drive combustion instabilities[14]. This burner arrangement has been described in previous work[15]. The burner nozzle is a stainless steel tube with an inside diameter of 2.18cm and a wall thickness of 1.8 mm. The premixing tube and ring stabilizer are positioned 20 cm (¼L) into the quartz main body in order to produce peak resonance. The flame is anchored on a ring (2.0 cm OD x 1.8 cm ID) located at the top of the nozzle.

Air and individual fuel constituent flow rates were controlled by mass flow controllers with mixing occurring well upstream of the burner nozzle. Various combinations of methane, propane and nitrogen were blended to provide test fuels for the lab scale burner.

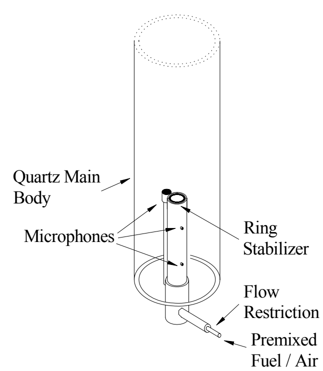

Fig 2. Schematic of Atmospheric Pressure Development

Results and Discussion

The lab-scale burner was operated on seven test fuels composed of various combinations of methane, propane and nitrogen as shown in Table 2. The average nozzle exit velocity was maintained at 1.5 m/sec while the flame equivalence ratio was varied from approximately $\phi = 0.6 - 1.3$. In addition to composition, Table 2 also provides the calculated Wobbe Index (BTU/ft^3)

for each of the fuels. Fuel A, which consisted of 100% CH4, was used as the reference fuel and the percentage variation of each fuel Wobbe Index from the reference is shown in the bottom of the table. Various amounts of propane and nitrogen are blended with methane to form fuels B - G.

Fuels B and F contain relatively large quantities of propane with 25% and 100% respectively, resulting in fuels with much higher heating values and thus higher Wobbe Indices (14% and 50% higher, respectively). Although not representative of typical natural gas, LNG, syngas or landfill gases they do provide an extreme boundary in which to evaluate the effects of fuel variability on combustion instabilities. Fuel D and E provide a more realistic fuel blend similar to what is commonly found in natural gas, or LNG supplies. Note that Fuel C, E and G are the same quantities of methane and propane as Fuels B, D and F respectively, only with nitrogen added to reduce the Wobbe Index back to the level of reference Fuel A. These diluted fuels now have Wobbe Indices well within the +/- 4% variation that is commonly observed in pipeline supply[4]. Table 3 is a list of the Wobbe and Schuster indices for each fuel along with the percent difference from the baseline fuel, Fuel A. Flame speed measurements used for the Schuster index were obtained from Cantera[18] using the C3 mechanism from Qin et al[17].

Table 2: Fuel Blends Tested In Lab-Scale Burner

	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E	Fuel F	Fuel G
Methane (%)	100	75	70	90	88.25	0	0
Propane (%)	0	25	20	10	8.25	100	62.3
Nitrogen %	0	0	10	0	3.5	0	37.7

Table 3: Wobbe and Schuster Index for test fuels

	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E	Fuel F	Fuel G
Wobbe	1362	1562	1369	1445	1370	2062	1377
% Diff		14.66	0.49	6.07	0.61	51.44	1.13
Schuster	1106	1208	1091	1143	1101	1505	1078
% Diff		9.28	1.37	3.37	0.43	36.09	2.52

Dynamic combustion instabilities are a continual concern for gas turbine systems utilizing lean pre-mixed combustion. Strong dynamics can produce pressure oscillations as much as 10% of the operating pressure. RMS pressure levels within the burner provide a means of characterizing the magnitude of the dynamic, or unstable, response of the burner to changes in fuel composition. The base case represents the observed response with 100% methane fuel, Fuel A. The other cases shown represent fuel blends with various levels of methane, propane and nitrogen. Again, note that although Fuels C, E and G have different fuel compositions, the Wobbe Index for each of these cases was made to match the baseline case (Wobbe $\approx$ 1360) in order to evaluate the ability of nitrogen dilution and Wobbe index matching on predicting the dynamic response of the burner. Fig 6 is a plot of the RMS pressure levels normalized to the maximum response of the burner on Fuel A as a function of equivalence ratio. A particular finding shown here is that for the baseline fuel (Fuel A) and Fuels D and E there is virtually no difference in the measured RMS pressure over the operating range investigated although there was a difference in the Wobbe number (6% for Fuel D). As the propane percentage is increased to 25% (Fuel B) there is a noticeable increase in the magnitude of the dynamic response. Further increasing the propane concentration to 100% (Fuel F) resulted in a continual increase in the magnitude of the dynamic response.

Of special interest are the measured response of Fuels C and G. These fuels were blended with high concentrations of propane and then diluted with nitrogen to reduce the Wobbe index to match Fuel A (WI = 1360). Results shown in Fig 6 indicate that although the Wobbe Index matched that of Fuel A, the dynamic response was essentially unchanged from its non-diluted fuel (Fuels B and F).

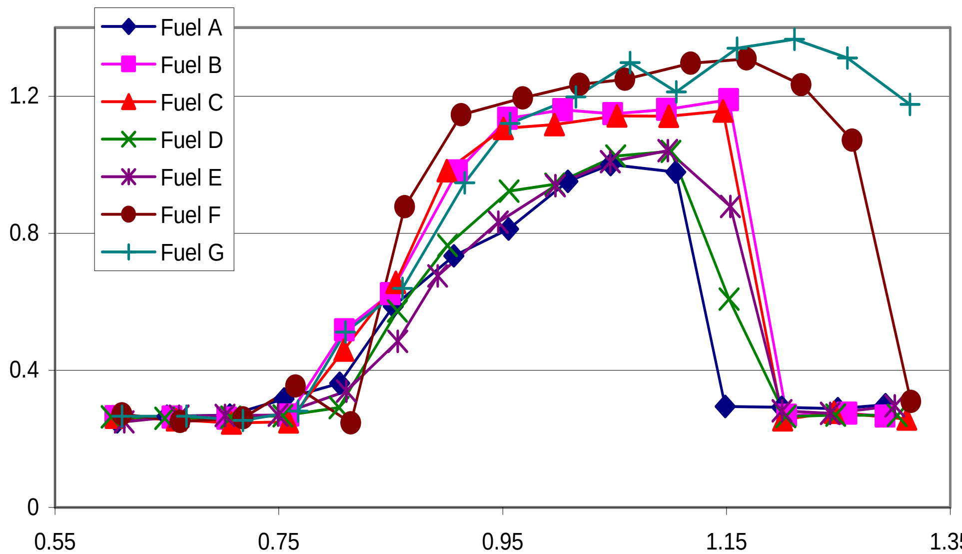

Figure 3: Dynamic response plotted as a function of equivalence ratio for varying fuel compositions.

Results from fuels C and G in which inerts were added in order to reduce the Wobbe seem to suggest that the Wobbe index is not sufficient at predicting a change in the dynamic response given a change in fuel composition. A similar finding is obtained for the Schuster Index. Fuels B, C, F and G had a similar response but significantly varied from that of Fuel A, while Fuels D and E had a very similar response as Fuel A. However, both fuels C and G had a Schuster Index closer to that of Fuel A. This would suggest a lack of correlation between the flame speed and the dynamic response although chemical time scales are an important mechanism in understanding combustion instabilities.

Figure 4 is a plot of the RMS pressure levels normalized to the maximum response of the burner on Fuel A (T_f = 2241 K) as a function of the theoretical adiabatic flame temperature. This plot would appear to suggest that the dynamic response of the burner was less affected by the actual fuel composition and more dependent upon the resultant flame temperature. Similar to Figure 3, there is very little difference in the dynamic response between fuels A, D and E although there was a difference in the Wobbe number (6% for Fuel D). As the propane percentage is increased to 25% (Fuel B) there is a noticeable increase in the magnitude of the dynamic response even at the same flame temperature. Further increasing the propane concentration to 100% (Fuel F) resulted in a continual increase in the magnitude of the dynamic response. This may suggest that changes in the chemical time scales alter the phase angle difference as to better align the heat release and acoustic pressure perturbations thus acting to increase the overall gain of the system. Although there appears to be a fairly good correlation of flame temperature with dynamic response, none of the commonly reported interchangeability factors include a component to account for flame temperature.

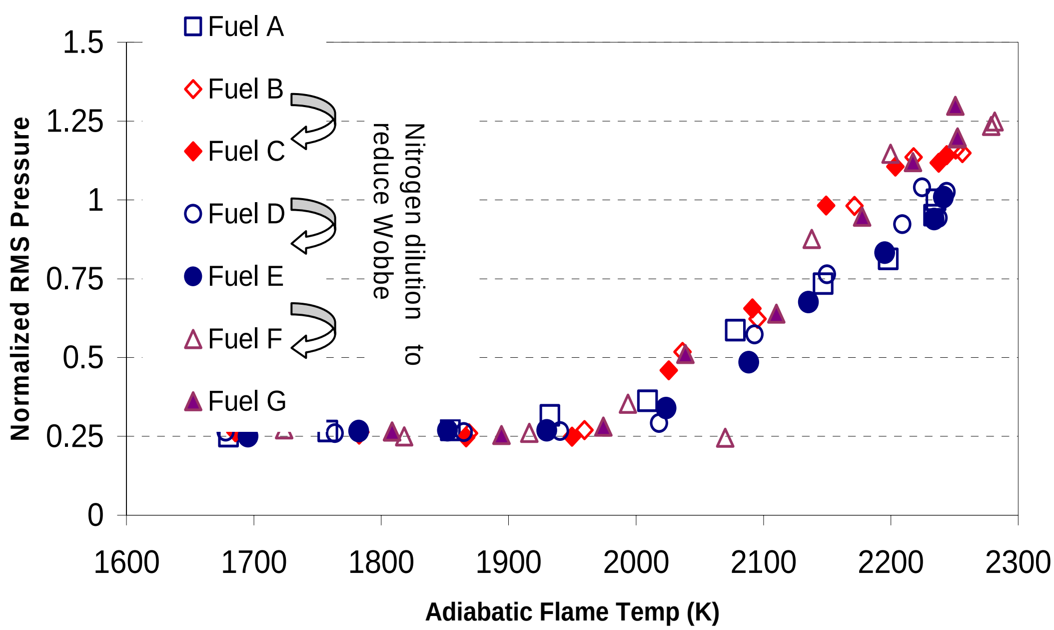

Figure 4: Dynamic response of the lab-scale burner as a function of the adiabatic flame temperature normalized to the maximum dynamic response of the burner on Fuel A

Conclusions

As interests in the use of alternatives to domestic natural gas, such as coal derived syngas, landfill gases and imported LNG, continues to increase, so will the need for predicting the interchangeability of these fuels. This is especially true in LPM gas turbine engines that are susceptible to lean blow-off, flashback and combustion instabilities. Current trends in industry are to utilize single or multiple index parameters to predict how changes in fuel composition may affect burner operation. However, these parameters were derived empirically from tests conducted on atmospheric burners and may not be applicable to high pressure turbine combustion.

While not fully detailed in this report, much of the emphasis today is on the development of computational models as opposed to simple parameters. These models take into account the complex thermodynamic and transport interactions of the gas mixtures. And by reducing these mechanisms to the most important parameters, it may be possible to incorporate their use in high-speed control systems to account for real-time changes in the fuel supply.

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